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The response of lake area and vegetation cover variations to climate change over the Qinghai-Tibetan Plateau during the past 30 years

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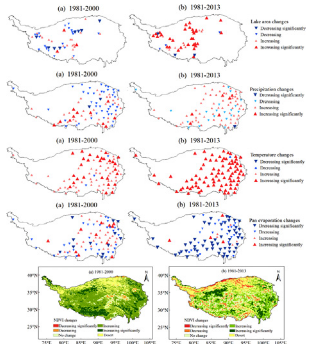
HIGHLIGHTS

- Lakes and vegetation are important components of terrestrial hydrosphere in the Qinghai-Tibetan Plateau.
- The lake areas of QTP increased significantly during the past 30 years and the rates have been sped up since 2000.
- Overall, the NDVI increased in the QTP during the past 30 years.
- The shifts in the temporal climate trend occurred around 2000 had led the lake area and vegetation coverage increasing.

GRAPHICAL ABSTRACT

Trends of lake areas, temperature, precipitation, pan evaporation and NDVI by using MK method during the past 30 years (a, 1981–2000; b, 1981–2013).



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ABSTRACT

Lakes and vegetation are important factors of the Earth's hydrological cycle and can be called an "indicator" of climate change. In this study, long-term changes of lakes' area and vegetation coverage in the Qinghai-Tibetan Plateau (QTP) and their relations to the climate change were analyzed by using Mann-Kendall method during the past 30 years. Results showed that: 1) the lakes' area of the QTP increased significantly during the past 30 years as a whole, and the increasing rates have been dramatically sped up since the year of 2000. Among them, the area of Ayakekumu Lake has the fastest growing rate of 51.35%, which increased from 618 km^2 in the 1980s to 983 km^2 in the 2010s; 2) overall, the Normalized Difference Vegetation Index (NDVI) increased in the QTP during the past 30 years. Above 79% of the area in the QTP showed increasing trend of NDVI before the year of 2000; 3) the air temperature increased significantly, the precipitation increased slightly, and the pan evaporation decreased significantly during the past 30 years. The lake area and vegetation coverage changes might be related to the climate change. The shifts in the temporal climate trend occurred around the year 2000 had led the lake area and vegetation coverage increasing. This study is of importance in further understanding the environmental changes under global warming over the QTP.

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1. Introduction

The Qinghai-Tibetan Plateau (QTP), with an average elevation of more than 4000 m, is the highest and largest highland in the world (Ijmker et al., 2012; You et al., 2008). The area is about 2.5 million km^2. The plateau is known as the "roof of the world" and "the third pole" (Ijmker et al., 2012). The dense distribution of lakes is a major feature of the QTP, and the total lake area accounts for about half of the China's total lake area (Zhu et al., 2010). Lakes are an important component of terrestrial hydrosphere, exchanging heat and water with the atmosphere (Xu et al., 2007). The QTP is also the headwater area for many large Asiatic rivers, such as Yangtze River, Yellow River, Mekong River, Yarlung Zangbo River, Indus River. As lakes in the QTP are rarely influenced by human activities due to the unique geographic location, therefore, they are extremely sensitive to climatic fluctuations and can be called an "indicator" of climate change, and the lakes are supposed as natural water bodies (Liu et al., 2009; Liu et al., 2013; Wan et al., 2014). This is of great theoretical and practical significance for the study of global environmental change and its response to climate change (Chen et al., 2014; Ke and Song, 2014; Zhang et al., 2014).

The vegetation coverage in the QTP is also called an "indicator" of climate change which plays a pivotal role in linking the biosphere, pedosphere, geosphere, hydrosphere, and atmosphere in the region, and even the whole of Asia (Huang et al., 2016). NDVI (Normalized Difference Vegetation Index) is an important indicator of vegetation coverage, and it can be used as an effective monitoring index between vegetation and natural environment (Band et al., 1993). The relationship between NDVI and climate had been extensively demonstrated at the regional scale and the global scale (Ji and Peters, 2003; Kim et al., 2012; Prasad et al., 2007; Sun et al., 2011; Zhao et al., 2011). Previous studies has reported that there were good relationships between the vegetation cover and climate change on the QTP. For example, Kato et al. (2004) found that the vegetation growth in the QTP was expected to be sensitive to climate change. Thus, the linkages among climate change, vegetation growth, and lake area changes might help to further understand the climate driving force to changes in lake, as well as the evaluation of regional ecological environment and sustainable development (Chen et al., 2014).

Satellite remote sensing is an important data source with advantages of vast covering area, rich information and higher repeated frequency (Fu and Liu, 2007; Wu and Zhu, 2008; Zhu et al., 2010). In recent years, satellite remote sensing has been successfully used to detect the changes in the vegetation coverage, lake level, area and volume in the QTP and other places around the world (Duan and Bastiaanssen, 2013a; Duan and Bastiaanssen, 2013b; Li et al., 2009; Yan and Zheng, 2015; Zhang et al., 2014). For example, Wang et al. (2014) monitored the changes of lake areas in the QTP during the past 30 years with satellite remote sensing data, and they found that 5 lakes whose original area was more than 1 km^2 have disappeared; Yamzhogyum Co is in constant shrinking, but the area of some lakes, such as Selin Co, is expanding. Zhang et al. (2014) analyzed the characteristics of lake level change from 1972 to 2012, and summarized the characteristics of the dynamic changes of typical lake water levels in the QTP under the background of climate warming in recent decades with multi-source remote sensing data.

However, some studies have focused only on the lake area changes with qualitative analysis, and the in-depth discussion on the dominant factors which affected the area of lakes is still lacking. Zhu et al. (2010) analyzed the lake area and water changes quantitatively in the past 34 years and their results indicated that the glacier melt caused by climate warming was the main reason which caused the rapid expansion of Nam Co Lake. Lei et al. (2013) reported that increased precipitation and runoff, and decreased lake evaporation were the main causes for the coherent lake growth and could contribute by about 70% of total increase in lake storage over the central QTP.

Therefore, a review of previous studies of the impacts of climate change on the lake areas over the QTP revealed that most of these studies ignored the response of lake areas and vegetation coverage changes to the climate change in the QTP, which is an important research gap. The research questions to be investigated in this study include: (1) Has the lakes' area increased in the QTP during the past 30 years? (2) Has the vegetation coverage restored in the QTP during the past 30 years? (3) Does the climate change affect the lakes' area and vegetation coverage over QTP during the past 30 years? This study is of importance in further understanding the environmental changes under global warming over the QTP.

2. Data and methodology

2.1. Study area

Qinghai-Tibetan Plateau (QTP) is located in the southwest of China with the territory area about 2.4 million km^2 (You et al., 2008). The climate in the plateau is marked by low temperature and strong solar radiation (Piao et al., 2011). The QTP lake region has the largest number of lakes in China. There are 1055 lakes, accounting for 39.2% of the total number of lakes in China (Piao et al., 2011; Xiao et al., 2013). In this study, a total of 51 lakes in the QTP were analyzed, of which 44 are mainly salt water lakes, and 7 are freshwater lakes. The characteristics of the studied 51 lakes in the QTP are presented in Fig. 1 and Table 1.

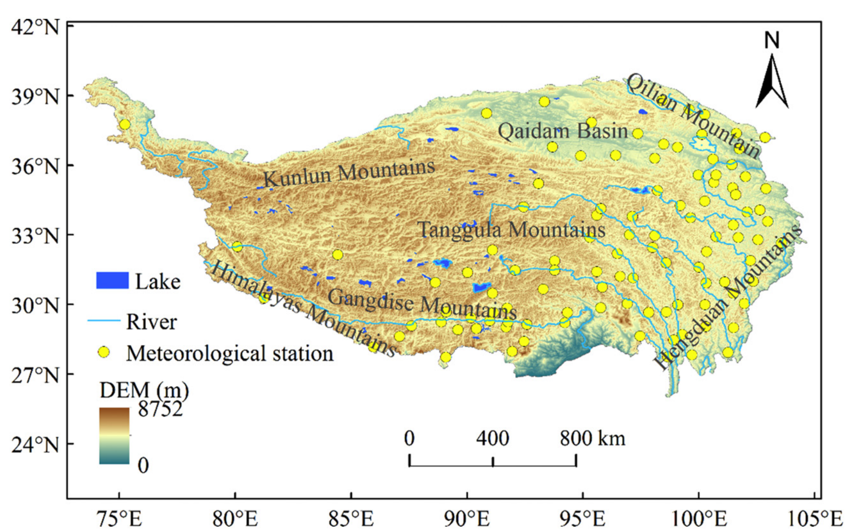

Fig. 1. Location of selected 51 lakes over the QTP and concerned meteorological stations.

Table 1
Characteristics of the 51 lakes in the QTP.

Name	Longitude (E)	Latitude (N)	Elevation (m)	Brackish	Lake areas (km^2)		Changes
					Past	Present	(%)
Anzi Co	87.10	31.02	4535	Salty	394.78	461.76	16.97
Aqikulu Lake	88.40	37.08	4250	Salty	358.76	495.14	38.01
Aruco	82.40	33.95	4940	Salty	104.5	103.74	−0.73
Ayakkum Lake	89.38	37.55	3870	Salty	618.21	935.68	51.35
Bangdag Co	81.55	34.95	4902	Salty	105.99	135.14	27.50
Cabo Co	84.20	33.37	4505	Salty	32.65	48.37	48.15
Cetacean Lake	89.42	36.33	4708	Salty	257.38	328.72	27.72
Chibzhang Co	90.27	33.38	4931	Salty	477.9	544.58	13.95
Cona	91.47	32.02	4800	Fresh	180.91	188.07	3.96
Cuodarima Lake	91.07	35.30	4775	Salty	86.19	95.56	10.87
Cuorendejia	92.57	35.23	4688	Salty	165.29	206.96	25.21
Dagze Co	81.55	34.95	4459	Salty	255.23	292.91	14.76
Dongqia Co	90.42	31.78	4616	Salty	48.76	71.83	47.31
Duoersuidong Co	89.87	33.38	4921	Salty	377.67	447.35	18.45
Duoma	84.95	32.95	4688	Salty	12.18	14.45	18.64
Eling Lake	97.70	34.90	4272	Salty	608.37	662.11	8.83
Guozhacuo	81.08	35.03	5080	Salty	246.55	247.7	0.47
Gyaring Co	88.33	31.13	4650	Salty	475.14	478.46	0.70
Hala Lake	97.58	38.27	4078	Salty	589.62	606.29	2.83
Hohxil Lake	91.12	35.57	4950	Salty	309.92	348.55	12.46
Jiarebu Co	87.78	32.20	4635	Salty	35.74	50.56	41.47
Jiezechaka Lake	80.90	33.95	4524	Salty	106.25	113.61	6.93
Kusai Lake	92.83	35.68	4470	Salty	267.43	289.09	8.10
Lexiewudan Lake	90.17	35.75	4854	Salty	223.61	273.01	22.09
Longmu Co	80.47	34.62	5002	Salty	99.18	104.95	5.82
Lumajangdong Co	81.62	34.03	4800	Salty	358.77	379.72	5.84
Luotuo Hu	81.95	34.43	5103	Salty	62.65	67.03	6.99
Mapam YumCo	81.47	30.67	4588	Fresh	408.44	408.42	0.00
Nam Co	90.55	30.70	4718	Salty	1944.61	2026.74	4.22
Ngangla Ringsto	83.10	31.55	4689	Salty	521.09	500.16	−4.02
Orba Co	81.03	34.53	5465	Salty	92.99	92.13	−0.92
Palung Co	83.57	30.87	5166	Salty	141.8	146.43	3.27
Pei Cuo	85.58	28.92	4590	Salty	275.32	268.82	−2.36
Peng Co	90.97	31.50	4522	Salty	137.22	177.66	29.47
Pengyan Co	88.20	35.88	4522	Salty	55.79	64	14.72
Pumoyum Co	90.42	28.57	5100	Fresh	285.53	291.44	2.07
Rinchen Shuptso	83.45	31.27	4756	Salty	182.93	188.12	2.84
Selin Co	89.00	31.83	4530	Salty	1755.17	2337.33	33.17
Senlicuo	84.07	30.42	5386	Fresh	142.41	142.26	−0.11
Sugan Lake	93.87	38.85	2795	Salty	100.79	107.89	7.04
Taro Co	84.10	31.12	4566	Fresh	484.42	486.55	0.44
Ulan Ul Lake	90.50	34.80	5100	Salty	527.76	624.63	18.35
Wuru Co	88.00	31.72	4548	Fresh	433.93	442.74	2.03
Xijirulan Hu	90.35	35.22	4769	Salty	286.41	351.04	22.57
Xuru Co	86.40	30.30	4718	Salty	207.09	210.55	1.67
Yamzhog YumCo	90.68	28.93	4441	Salty	586.38	554.12	−5.50
Ze Co	79.78	34.15	4961	Salty	113.59	118.37	4.21
Zhaling Lake	97.27	34.92	4294	Fresh	520.28	530.59	1.98
Zharinam Co	85.63	30.92	4613	Salty	1000.16	1004.63	0.45
Zigetang Co	90.85	32.07	4561	Salty	198.89	234.11	17.71
Zonag Lake	92.00	35.53	4800	Salty	259.27	271.6	4.76

2.2. Datasets processing

Meteorological data such as air temperature, precipitation and pan evaporation were collected from 86 meteorological stations in the QTP from the China Meteorological Science Data Sharing Service Network.

The NDVI dataset at a spatial resolution of 8 km × 8 km and 15-day interval were derived from GIMMS (global inventory modeling and mapping studies) group. The dataset spanned from 1982 to 2013. It has been calibrated for sensor shift, cloud test and removed the effects of solar zenith angles and other factors (Piao et al., 2011).

The lake area data were derived from Landsat satellite imagery data. Landsat is a NASA land satellite program and had launched eight missions since July 23, 1972. The data in this paper are mainly from Landsat 4, 5, 7 and 8. The remote sensing software ENVI was used to extract the lake area for the studied period.

The spectral water index was a single number derived from an arithmetic operation (e.g., ratio, difference, and normalized difference) of two or more spectral bands. An appropriate threshold of the index was then established to separate water bodies from other land-cover features based on the spectral characteristics. The design of a spectral water index was based on the fact that water absorbs energy at near-infrared (NIR) and shortwave-infrared (SWIR) wavelengths (Ji et al., 2009). In this study, the lake area was extracted by water index method in multi-spectral remote sensing water identification method, which includes: Normalized Difference Water Index (NDWI), Normalized Difference Vegetation Index (NDVI), Normalized Difference Snow Index (NDSI) and Ratio Vegetation Index (RVI) (Gu et al., 2007). The NDWI method is adopted in our paper which has been widely used in the world (Gao, 1996; Ji et al., 2009; McFeeters, 1996).

Adopting the format of the Normalized Difference Vegetation Index (NDVI), McFeeters (1996) developed the normalized difference water index (NDWI), defined as

$$\mathrm{NDWI} = \frac{\rho_{\mathrm{GREEN}} - \rho_{\mathrm{NIR}}}{\rho_{\mathrm{GREEN}} + \rho_{\mathrm{NIR}}}$$

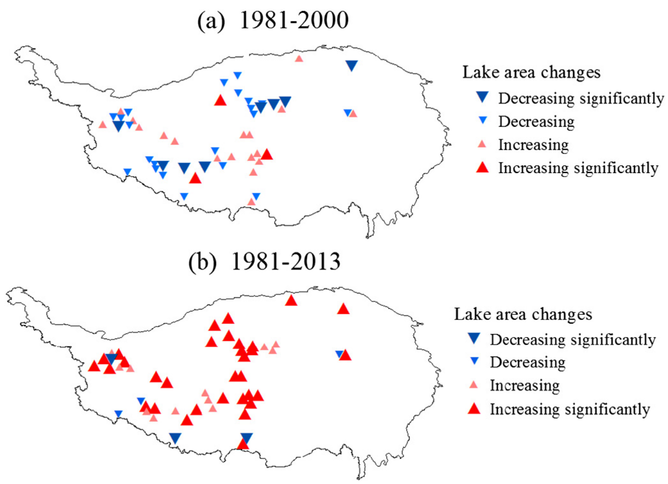

Fig. 2. Trends of annual lake area changes in the QTP by using MK method during the past 30 years (a, 1981–2000; b, 1981–2013).

where NDWI is water index; GREEN is green band; NIR is near infrared band. The method includes the following steps: View the spectral curve after the band operation, set reasonable threshold value, count the number of pixels within the threshold value, and then according to the resolution of the satellite image, calculate the area value of the lake.

2.3. Methods

The non-parametric rank-based Mann–Kendall (MK) test was used to analyze the trends of climate and vegetation coverage change in this study (Kendall, 1975; Mann, 1945). Non-parametric tests make no assumptions about the distribution of data and are useful for detecting monotonic trends (Huth and Pokorna, 2004; Nepal, 2016). In addition, the MK test is based on sign differences rather than value, and is thus robust to the effect of extreme values and outliers (Helsel and Hirsch, 2002). It is widely used for trend analysis (Zhang et al., 2011b). The Kendall rank correlation coefficient, commonly referred to as Kendall's tau (τ) coefficient, is used to measure the association between two measured quantities. The 95% confidence interval was used as a threshold to classify the significance of positive and negative MK trends (Xu, 2001). The non-parametric Sen's method was used to estimate the true slope of the identified trends (Sen, 1968).

Simple linear regression was used in this paper for long-term linear trend test as well. The simple linear regression method is a parametric *t*-test method, which consists of two steps, fitting a linear simple regression equation with the time t as independent variable and the hydrological variable (i.e. precipitation or streamflow in this study) as dependent

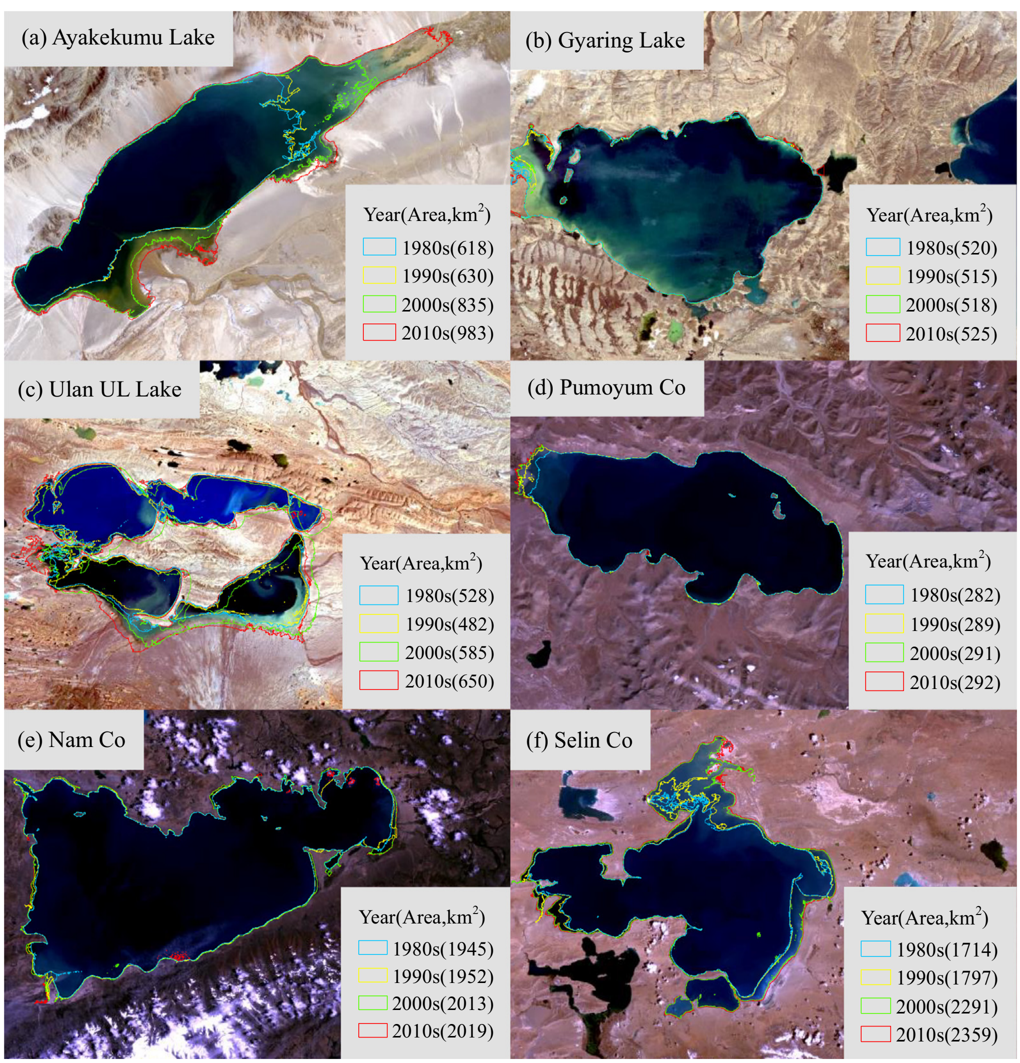

Fig. 3. The spatial changes of lake area for the selected six lakes during the past 30 years.

variable; testing the statistical significance of the slope of the regression equation by the *t*-test (Xu, 2001; Zhang et al., 2009).

3. Results and discussion

3.1. The temporal and spatial variation of lake area in the QTP

Fig. 2 showed that there were 30 lakes have shown area decrease and 21 lakes with area increase during the period of 1981–2000 by using Mann-Kendal method. There were 8 lakes have shown significant area decrease during this period, while there were 3 lakes with significant area increase at 5% significance level. As for the period of 1980–2013, most of the lake areas have increased and 32 lakes' areas have increased significantly. However, there were only 6 lakes' areas decreased during this period.

In order to reveal the spatial and temporal variabilities of the lake areas during the past 30 years, 6 lakes in the central QTP were selected for illustration purposes (Fig. 3). It can be found that the lake areas increased obviously for the selected 6 lakes during the past 30 years. Among them, the area of Ayakekumu Lake has the fastest growing rate of 51.35%, which increased from 618 km^2 in the 1980s to 983 km^2 in the 2010s. While the Gyaring Lake was the slowest growth lake with the area increased from 520 km^2 in the 1980s to 525 km^2 in the 2010s. As for the lakes of Nam Co and Selin Co, Nam Co was the second largest saltwater lake in China and Selin Co was the third largest salt lake in China in before the year of 2000. However, the area of Selin Co increased rapidly after the year of 2000 making it the second largest saltwater lake in China now, and Nam Co became the third largest saltwater lake in China although it increased from 1845 km^2 in the 1980s to 2019 km^2 in the 2010s. Therefore, it can be inferred that the growth rate of the lake area for Selin Co was obviously higher than that of Nam Co after 2000.

Fig. 4 showed the temporal variation of 6 lake areas during the past 30 years. It can be seen that the 6 lakes' area increased significantly during the past 30 years, although the lake areas decreased in the 1990s. The findings were consistent with other studies (Li et al., 2009; Yan and Zheng, 2015). Yan and Zheng (2015) analyzed the dynamic changes of the saline lake surface areas from 1973 to 2010 in the QTP and they found that the total surface areas of these saline lakes increased, especially since around 2000, and the total surface areas increased by 47% during 1973–1977 to 2008–2010. While the saline lake areas decreased during 1973–1977 to 1989–1992 in the northern and middle parts of the Tibet Plateau and nearly all the saline lakes expanded since around 2000. Zhang et al. (2014) also reported that the number of lakes with areal extent of 1 km^2 decreased between the 1970s and 1990, followed by a clear increase from 1990 to 2010. Moreover, ninety-nine new lakes

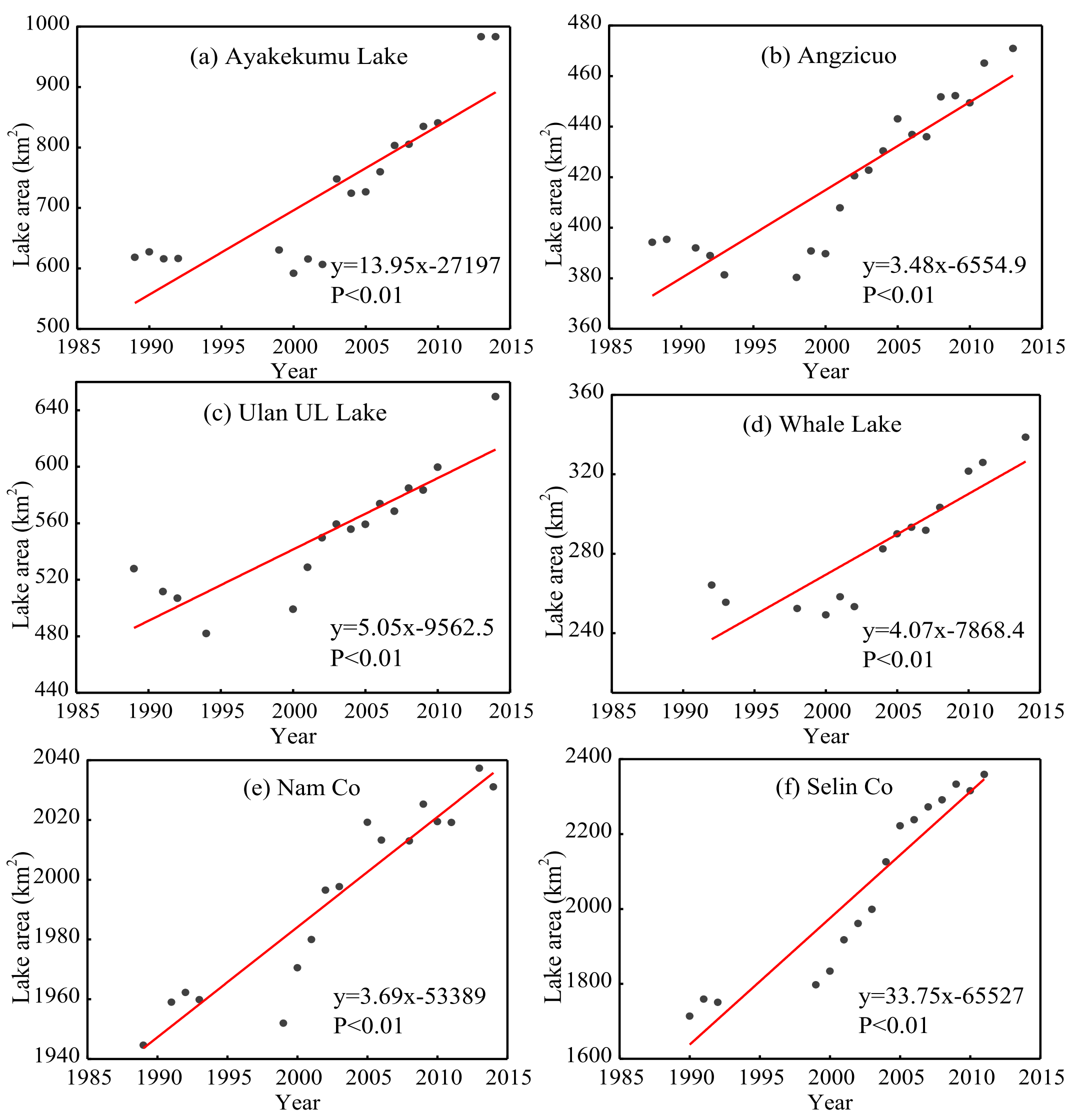

Fig. 4. The temporal variation of lake area for the selected six lakes during the past 30 years.

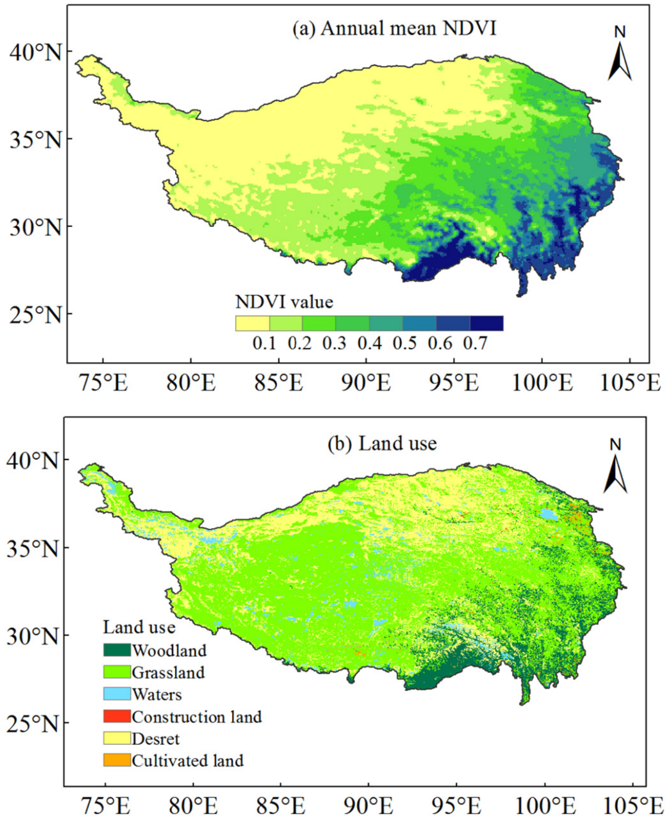

Fig. 5. Annual mean NDVI in the QTP during 1981–2013 (a) and the land use spatial distribution in the year of 2010 (b).

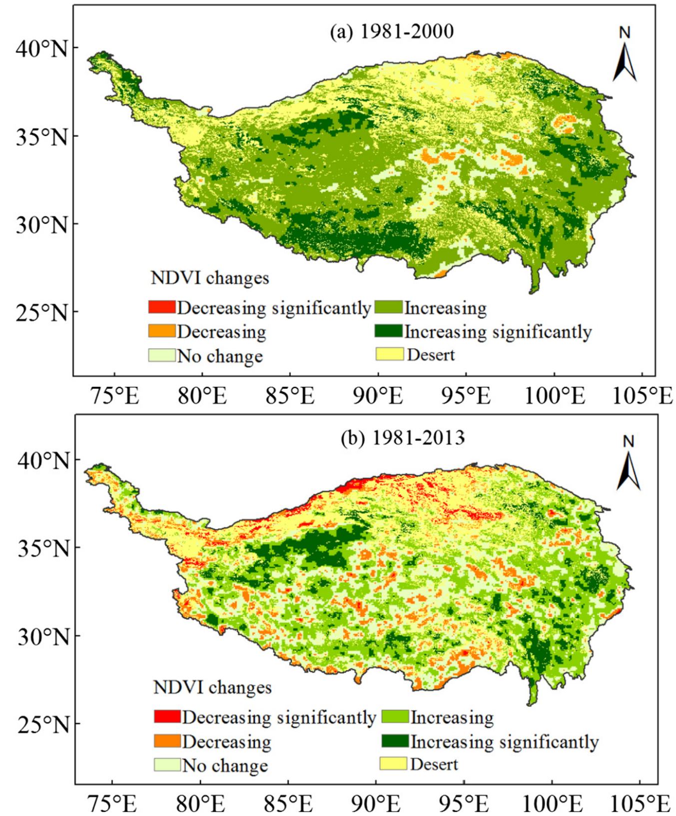

Fig. 6. Trends of annual mean NDVI in the QTP by using MK method during the past 30 years (a, 1981–2000; b, 1981–2013).

were identified between the 1970s and 2010 and 71 of which were found between 1990 and 2010.

3.2. Trends of vegetation coverage in the QTP during the past 30 years

With a mean elevation of approximately 4000 m above sea level, the annual mean NDVI has not only generally small value but also different spatial distributions (Fig. 5a). It can be found that the grasslands occupy nearly three quarters of the land surface of the QTP (Fig. 5b). Higher NDVI value can be found in the Hengduan Mountains with rich forest, however, lower NDVI value appeared in the north of QTP where distributes large desert (Fig. 5).

Fig. 6 showed the long-term trends of NDVI during the period of 1981–2013. It can be found that the NDVI exhibits obvious increasing trends for the whole QTP during the period of 1981–2000, especially in the mountainous areas of southern Tibet region. According to the statistical analysis of pixel, the number of pixels with increasing trends of NDVI was 79% of the total number of pixels, of which 26.4% of the pixels increased significantly. However, the number of pixels with decreasing trends of NDVI was 5.58% which indicated that the vegetation recovery in the 1990s was better than that of 1980s (Fig. 6a). Compared with the period of 1981–2000, there were obvious deterioration in vegetation in general terms, especially in the north of the QTP during the period of 1981–2013. The increasing trends can be found in the Kunlun Mountains, Qilian Mountains, Gangdise Mountains and Hengduan Mountains during this period. The pixels of NDVI with increasing trends in the whole region were less than half of the total number of pixels, of which 19.54% of the pixels showed significant increasing trends. While the proportion was as high as 31.17% for the pixels with decreasing trends and of which 14.73% decreased significantly (Fig. 6b). Huang et al. (2016) also found the grassland growth has improved obviously through most of the Plateau from 1986 to 2000 and the condition of grassland growth became worse, especially in the arid regions across QTP from 2000 to 2011.

3.3. Trends of climate change in the QTP during the past 30 years

Assessing the impact of climate change on the lake area is very important for water resources management and ecological protection. As the QTP is one of the most sensitive areas of ecological environment change and the lake area variations are highly vulnerable to the climate change. It can be found that the areal mean precipitation has increased slightly during the past 50 years, while the annual mean temperature increased significantly and the pan evaporation decreased significantly (Fig. 7). Fig. 8 showed the spatial distribution of annual mean precipitation trends in the QTP by using MK method during the past 30 years. The results showed that the precipitation increasing trends can be found in the southern part of the QTP and decreasing trends appeared in the northern part during the period of 1981–2000. As for the period of 1981–2013, the precipitation increased in most areas of the QTP and the number of the rain gauge stations with increasing trend has increased markly than that of 1981–2000.

Fig. 9 showed the spatial trends of annual mean temperature in the QTP during the past 30 years. It can be found that the annual mean temperature increased almost in the whole QTP during the period of 1981–2000 and 1/3 of the gauge stations showed significant increasing trends in this period. While the temperature increased significantly almost in the whole region of the QTP during the period of 1981–2013. Therefore, it can be inferred that the temperature increased more quickly after the year of 2000.

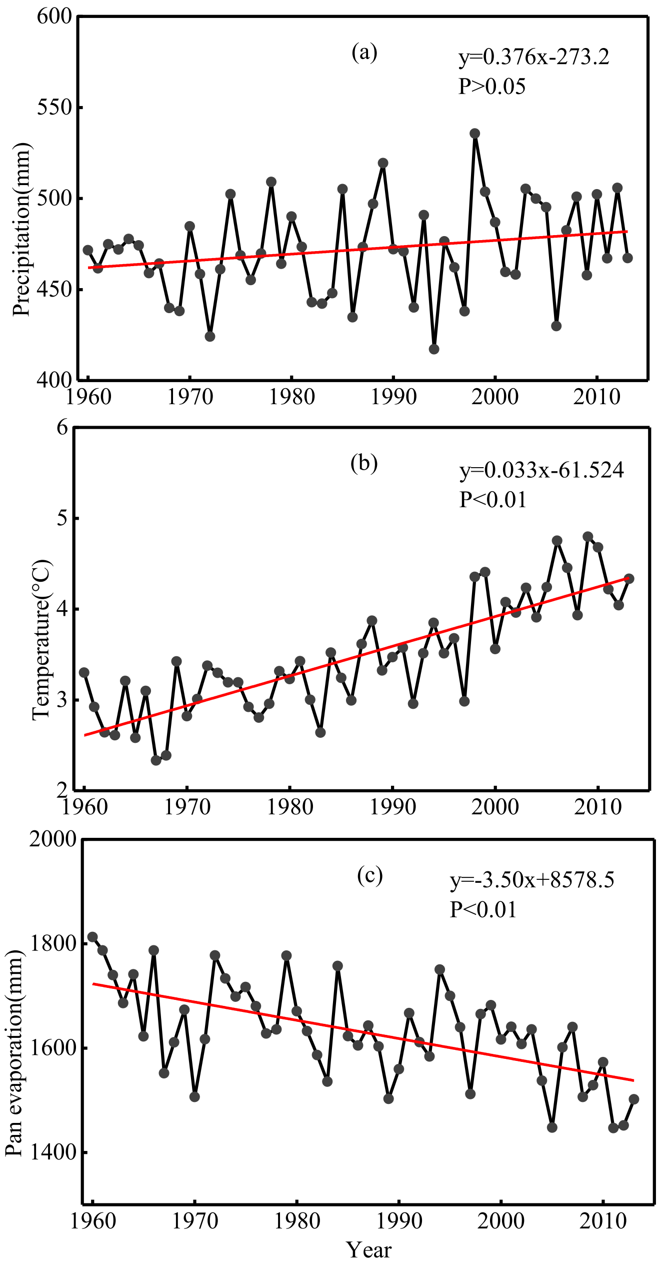

Fig. 7. The changes of areal mean precipitation (a), air temperature (b) and pan evaporation (c) over the QTP during the past 30 years.

The annual mean pan evaporation in the QTP during the past 30 years was also analyzed and shown in Fig. 10. It can be found that half of the gauge stations in the QTP showed downward or upward trends in the year of 1981–2000, and among them, around 10% of the gauge stations increased or decreased significantly. While the number of the gauge stations with decreasing trends of pan evaporation in the period of 1981–2013 was obviously more than that the period of 1981–2000 and the number of gauge stations with decreasing trends increased from 10% to 66% during 1981–2000 to 1981–2013.

These results were similar to the previous researches, for example, Li et al. (2010) reported that the QTP had experienced significant warming and wetting trends during the period 1961–2007 and it had exhibited increases in the precipitation amount, the number of precipitation days and extreme high temperature events. Li et al. (2015) also found that precipitation experienced a statistically insignificant increasing trend at a rate of 6.32 mm/10a, and the air temperature increased significantly at the rate of 0.32 °C/10a in the Yarlung Zangbo River which is the largest river system in the QTP.

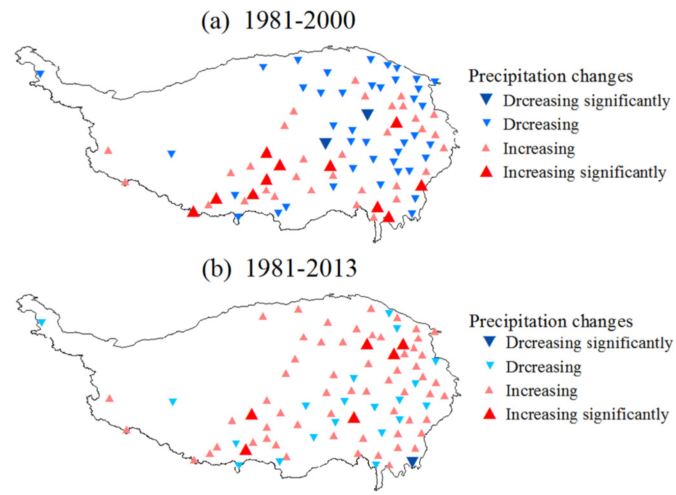

Fig. 8. Trends of annual mean precipitation in the QTP by using MK method during the past 30 years (a, 1981–2000; b, 1981–2013).

3.4. The response of lake area and vegetation coverage to the climate change

Both of the lakes' surface area and vegetation coverage are the indicators of climate change and climate variability in the QPT. Moreover, vegetation plays a critical role in regulating the ecological and hydrological functions of the QTP. Fig. 11 showed the long-term changes of areal annual mean NDVI in the whole QTP during the period of 1981–2013. It can be found that the NDVI increased significantly in the 1980s and then maintained a higher equilibrium in the 1990s, however, the NDVI decreased after the year of 2000. Although the annual mean NDVI varied greatly in the QTP, it takes on a rising trend generally. It can also be found that the annual variabilities of NDVI was in good line with temperature (Fig. 11a). The relationship between NDVI and precipitation seems contradictory (Fig. 11b), however, the relationships between NDVI, temperature and precipitation were not stable during the past 30 years which indicated that the factors affecting the vegetation were various in the QTP.

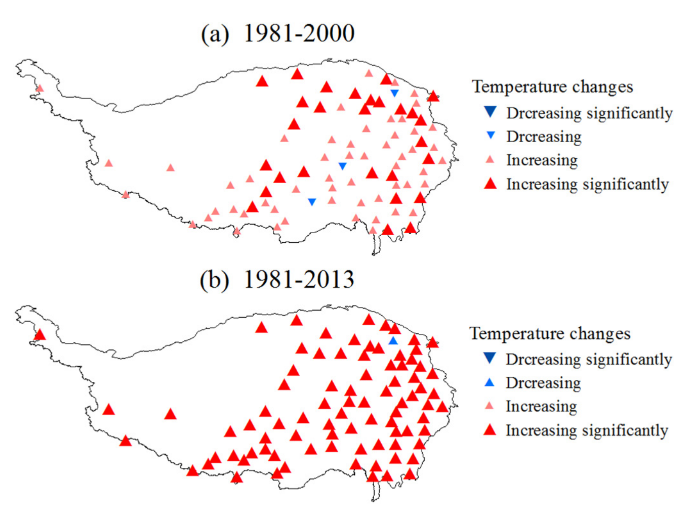

Fig. 9. Trends of annual mean temperature in the QTP by using MK method during the past 30 years (a, 1981–2000; b, 1981–2013).

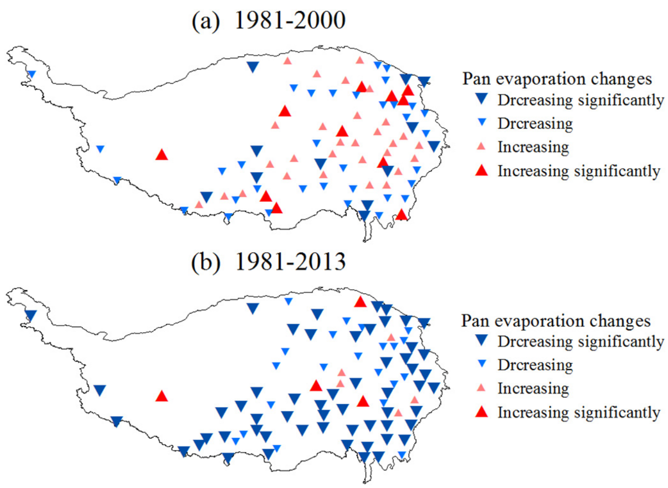

Fig. 10. Trends of annual mean pan evaporation in the QTP by using MK method during the past 30 years (a, 1981–2000; b, 1981–2013).

The precipitation of the QTP was increasing and the annual mean pan evaporation was decreasing significantly; and the climate warming and wetting resulted in the vegetation restoration in the QTP during the past 30 years. Overall, decreased evaporation and enhanced precipitation increased the area of lakes in the QTP, and increased temperature and enhanced precipitation favored vegetation growth in the QTP. The result was the same as previous studies who claimed that the most likely reason for the expansion of Qinghai Lake and vegetation restoration was the increasing precipitation, temperature and decreasing evaporation due to the change of summer monsoon (Huayu et al., 2010; Wan et al., 2014). Zhu et al. (2010) thought that the lake area changes were closely linked to climate change under global warming. Li and Shi (2000) found that the NDVI was significantly correlated with both precipitation and temperature. However, it should be noted that the glacial retreats caused by warming is an important factor in the increase of lake area and elevation of water level, for example, the rise in the water level of Nam Co and Selin Co might be related to the increase of meltwater (Li, 2012). The ecosystem environment recovery not only reflected the changing trend of warm and wet climate but also was a response of the ecological protection project of the Key Ecological Function Zone in the Three-River Headwaters (Zhu et al., 2015). Therefore, the influencing factors of lake area and vegetation coverage changes are very complex in the QTP (Huang et al., 2016; Yan and Zheng, 2015; Zhang et al., 2011a).

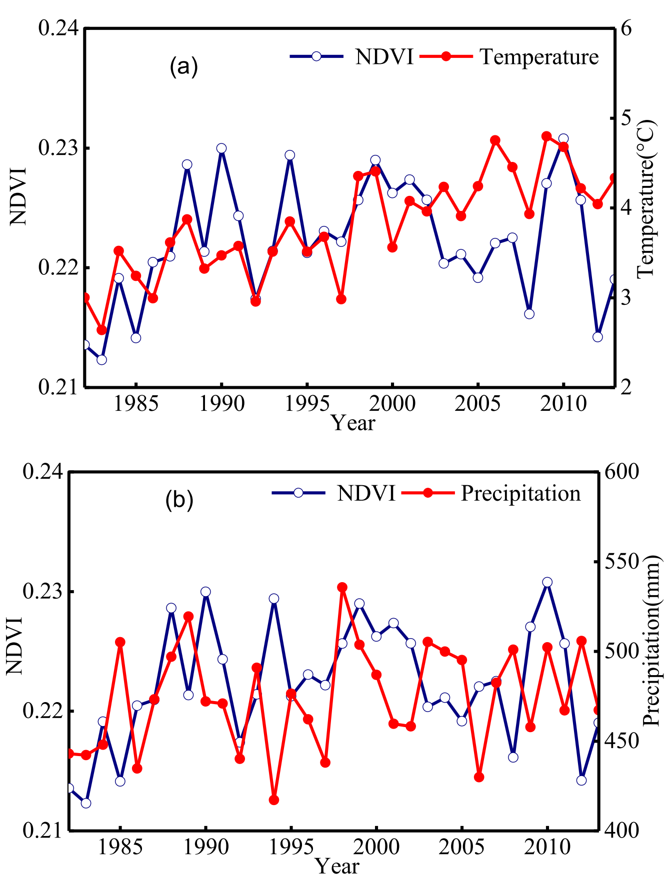

Fig. 11. Variabilities of annual mean NDVI, precipitation and temperature in the QTP during the period of 1981–2013.

It can be found that pronounced shifts in the temporal climate trend occurred around the year 2000 which had arose the lake areas and vegetation coverage change greatly in the QTP. The lakes' area increased significantly since the year of 2000 and the vegetation coverage had also undertaken a great change since the year of 2000. The vegetation coverage increased in the south of the QTP, while it decreased significantly in the north of QTP. Huang et al. (2016) also reported that a wetter and warmer climate improved grassland growth through most of the Plateau from 1986 to 2000, while the drier and hotter climate disfavored grassland growth, especially in the arid regions across QTP from 2000 to 2011.

4. Conclusions

In this study, the long-term variations of lake areas, vegetation coverage and associated climate changes in the QTP were analyzed by using MK method with the aim of exploring the climate transformation during the past 30 years. Main conclusions drawn from the study are summarized as follows:

(1) Overall, the lake areas increased significantly during the past 30 years in the QTP,and increasing magnitude for the lake areas accelerated after the year of 2000. Among them, Ayakekumu Lake was the fastest growing lake with area increased from 618 km^2 in the 1980s to 983 km^2 in the 2010s at a rate of 51.35%.
(2) The vegetation coverage of the QTP increased in the whole QTP during the past 30 years and the vegetation coverage in the southeast was obviously better than that in the northwest. The NDVI exhibits obvious increasing trends for the whole QTP during the period of 1981–2000, 79% of the total number of pixels showed increasing trends, of which 26.4% of the pixels increased significantly. However, the number of pixels showed increasing trends in the whole region was less than half of the total number of pixels during the period of 1981–2013. The proportion was 31.17% for the pixels with decreasing trends during this period.
(3) The precipitation and temperature of the QTP showed increasing trend during the past 30 years and the temperature in most areas increased significantly, especially after the year of 2000. While the pan evaporation decreased significantly during the year of 1981–2013. It can be inferred that the lake area and vegetation changes might be related to climate change. The shifts in the temporal climate trend occurred around the year 2000 had arose the lake areas and vegetation coverage change greatly in the QTP. The lakes' area increased significantly since the year of 2000 and the vegetation coverage had also undertaken a great change since the year of 2000.

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